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Hydraulic Analysis of Micro-irrigation Laterals: a New Approach

M.S.M. Amin and Z.J. Svehlik[1]

Department of Field Engineering,
Faculty of Engineering,
Universiti Pertanian Malaysia,
43400 UPM Serdang, Selangor, Malaysia.
[1]*Institute of Irrigation Studies*
Southampton University
SO9 5NH United Kingdom.

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ABSTRAK

Pendekatan semasa analisis hidraul saluran sisi mikro-pengairan telah disesuaikan dari rekabentuk pengairan percik dimana saiz paip dan kadaralir adalah besar. Luahan penyebar dan kehilangan turus pada sambungan penyebar dianggap seragam, atau formula empirikal digunakan sedangkan kesan suhu diabaikan. Penggunaan formula itu tidak bertepatan dengan kehilangan turus sebenar pada saluran sisi poliethilena kecil dalam julat nombor Reynolds yang biasa ditemui dalam mikro-pengairan, dan seharusnya tidak digunakan bagi analisis yang tepat. Persamaan Darcy-Weisbach dengan faktor geseran gabungan untuk tonjolan penyebar serta paip licin digunakan dalam penilaian turus langkah demi langkah dapat memberi keputusan yang lebih baik daripada kaedah semasa. Pendekatan baru ini juga mengambil kira variasi pembuatan penyebar serta kesan suhu ke atas luahan penyebar dan kadar alir dalam paip. Kaedah ini tidak memerlukan lagi penggunaan satu faktor untuk membahagi aliran, dan panjang paip setara untuk kehilangan turus disebabkan oleh tonjolan sambungan penyebar.

ABSTRACT

The current approach in hydraulic analysis of micro-irrigation laterals has been derived from sprinkler irrigation design where pipe sizes and flow rates are large. The approach assumes uniform emitter discharge and emitter barb head loss, or uses empirical formulae which are not applicable to micro-irrigation systems due to errors caused by ignoring the effect of water temperature. The formulae do not fit the actual head loss in small diameter polyethylene pipes for the range of Reynolds number normally encountered in micro-irrigation and should not be used for accurate analysis. The Darcy-Weisbach equation with a combined friction factor for the smooth pipe and local loss due to emitter connection used in a step by step evaluation of head loss gives more accurate results than the current method. The new approach also considers emitter manufacturing variation, and the effect of temperature changes on emitter discharge and lateral flow rates. This approach makes the use of equivalent pipe length for emitter connection head loss and a factor for dividing flow unnecessary.

Keywords: micro/trickle/drip irrigation, pipe flow hydraulics, lateral design, emitter connection head loss, friction factor, isolated roughness flow regime

INTRODUCTION

Accurate evaluation of energy losses in a micro-irrigation system is necessary for maximum economy at a chosen uniformity of irrigation. However, the conventional approach in hydraulic analysis is inaccurate because of some simplifying assumptions derived from sprinkler irrigation design where pipe sizes and flow rates are large. The use of an empirical formula which ignores the effect of water temperature on the polyplastic pipe and emitters has caused serious errors (Von Bernuth 1989).

Pipe friction head loss in a micro-irrigation system is normally calculated using either the Hazen-Williams formula or the Darcy-Weisbach equation with friction factor taken from Blasius equation for smooth pipes. The head loss due to emitter connection to the lateral is assessed separately from pipe friction, and expressed as an equivalent length which is then included in the head loss equation. The head loss is next multiplied by a reduction coefficient for multiple outlets to account for reduced flow along the lateral.

The assumption that emitter discharge and local loss due to emitter barb protrusion are constant throughout the length of the lateral is incorrect. Ignoring the variability in emitter discharge caused by changes in water temperature and emitter barb protrusion has underestimated and in some cases overestimated the actual head loss in the field. Thus the above-mentioned factors should be considered in the analysis in order to improve the determination of energy drop by friction and water application efficiency.

EMPIRICAL FORMULAE

The most common empirical formula for calculating total head loss in a lateral is the Hazen-Williams formula. When reduction coefficient for multiple outlets F and local losses due to emitter protrusion expressed in equivalent length Le are included, the equation becomes

$$Hf = 3142.43\ D^{-4.871} (Q/C)^{1.852}\ F\ (L + Le) \qquad (1)$$

where Hf is head loss in m, D is internal pipe diameter in mm, Q is the total flow rate in l/h, C is the Hazen-Williams roughness coefficient, F is dimensionless and L is lateral length in m.

Substituting for the average emitter discharge qa = Q/N at the average operating pressure head and the total number of emitters is length divided by emitter spacing, N = L/S, the equation becomes

$$Hf = 0.621\ D^{-4.871}\ [(100.qa)/(S.C)]^{1.852}\ F\ (L + Le)^{2.852} \qquad (2)$$

where qa is in l/h and S is the emitter spacing in m.

DARCY-WEISBACH EQUATION

The Darcy-Weisbach equation for head loss in a lateral pipe may be expressed as

$$Hf = 6.376\ \lambda\ L\ Q^2/D^5 \qquad (3)$$

In the conventional approach, the friction factor λ is normally taken from Blasius equation for smooth pipe,

$$\lambda = 0.3164\ Re^{-0.25} \qquad \sim Re < 10^5 \qquad (4)$$

where Re is Reynolds number. Substituting for λ and Re at 20° C, Eqn. 3 becomes

$$Hf = 0.4664\ D^{-4.75}\ (q/s)^{1.75}\ F\ (L + Le)^{2.75} \qquad (5)$$

Other studies on friction factor for flow in small polyethylene pipes without emitters show that λ-Re lies above the Blasius smooth curve.

Bezdek and Solomon (1978) derived λ for smooth half-inch PE pipe valid for Re between 4000 and 14,000 as follows:

$$\lambda = 0.0286\ e^{e-(1.9875\ E\text{-}4)\ Re} \qquad (6)$$

Dent (1985) obtained a relationship as follows:

$$\lambda = 0.004\ e^{6.739}\ Re^{-0.123} \qquad (7)$$

Kochanek *et al.* (1986) found

$$\lambda = 0.492\ Re^{-0.29} \text{ valid for } Re > 2300 \qquad (8)$$

When linearized in the form of Eqn. 4, Eqn. 6 becomes

$$\lambda = 0.529\ Re^{-0.299} \qquad (9)$$

and Eqn. 7 becomes

$$\lambda = 0.414\ Re^{-0.267} \qquad (10)$$

Eqns. 8, 9 and 10 can be used to substitute the friction factor from Blasius Eqn. for determination of head loss in smooth PE laterals.

NEW APPROACH

A new approach in the hydraulic analysis of micro-irrigation laterals is to use the Darcy-Weisbach equation in a step by step analysis with a combined friction factor for pipe friction and emitter protrusion in the pipe. The combined assessment of friction loss was suggested by Decroix and Malaval (1985). Better accuracy is obtained than when using the equivalent length of pipe for emitter connection pressure loss. Le in Eqn. 1 is not a real characteristic of the emitter and it varies with lateral flow rate and emitter spacing. The combined friction factor is

$$\lambda p = \lambda s + \lambda r \tag{11}$$

where λp, λs and λr are friction factors for pipe with isolated roughness, smooth pipe and roughness element, respectively. The combined value λp may be obtained from experiments for various pipes sizes, emitter protrusion shapes and emitter spacings. A typical result for this kind of study is shown in *Fig. 1* for emitter protrusion of 5 mm in a 14.3 mm ID PE tubing at various spacings.

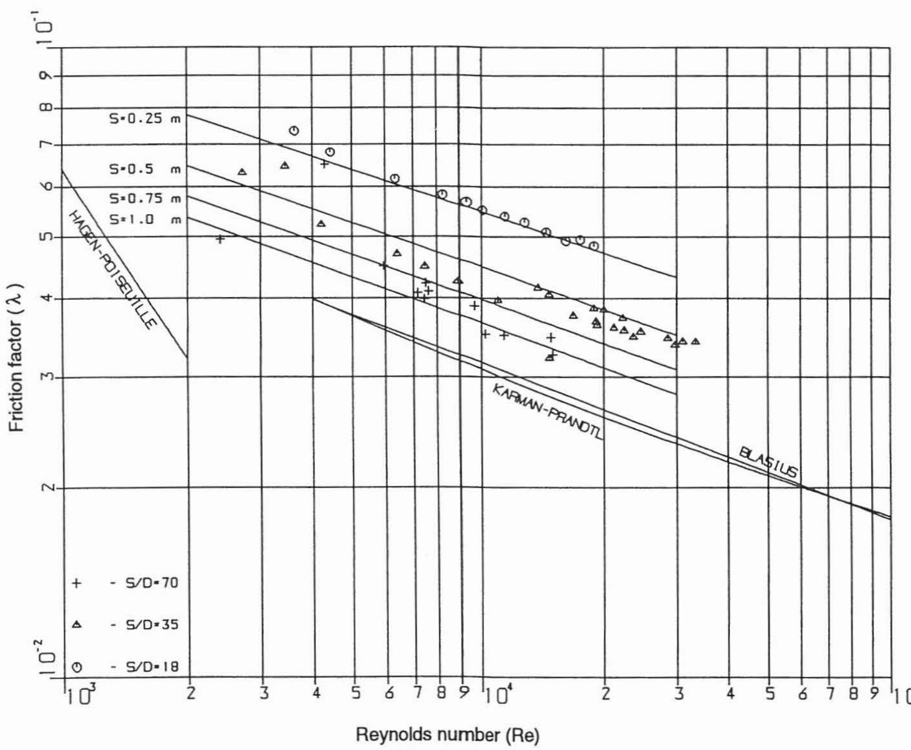

Fig. 1. Friction factor for isolated roughness flow

In the step by step approach, the actual emitter discharge rate as affected by elevation and temperature changes, is considered instead of the nominal or average discharge rate. *Fig. 2* shows a schematic of the step by step approach. The upstream operating pressure head, H_{i+1}, is given by

$$H_{i+1} = H_i + Hf_i + He_i \qquad (12)$$

where He is positive for a rising lateral from the manifold and negative for a lateral running downhill. For low angles tan θ equals sine θ . Thus He is the product of lateral reach slope and emitter spacing.

Water temperature in micro-irrigation tubing can be up to 50° or even 60°C, especially in the laminar portion of the lateral length. Flow rates in the tubing and some sensitive emitters are expected to increase due to expansion of the plastic material. Peng *et al.* (1986) found that a 10% increase in total discharge will cause an 18% increase in total friction drop at the end of the lateral line. A measure of changes in the pipe dimensions is given by a linear coefficient of thermal expansion, ∝ in cm/cm per degree C.

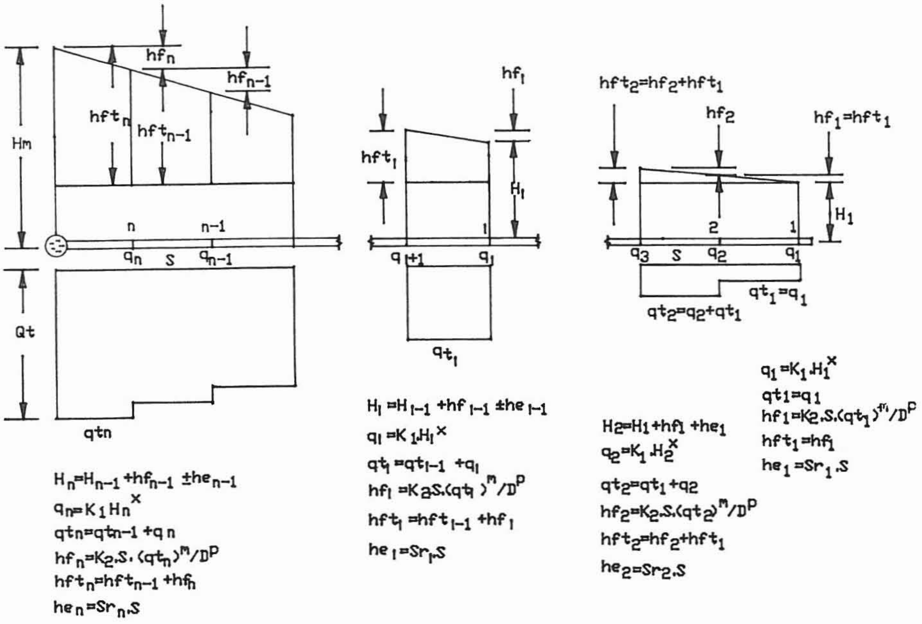

Fig. 2. Step by step method of determining energy loss using friction factor for isolated roughness flow

$$\alpha = (\Delta L/L)/\Delta T \quad (13)$$

$$\text{or } D_2 = \alpha (T_2 - T_1) D_1 + D_1 \quad (14)$$

Solomon (1985) suggested that water temperature at any position along the lateral length may be estimated by

$$T_i = (1 - L_i^{0.644}) (T_1 - T_n) + T_n \quad (15)$$

where $(T_1 - T_n)$ is the difference in water temperature from both ends of the laterals. For example, if the total length in 200 m, $T_n = 24°C$, $T_1 = 42°C$, the water temperature at 50 m from the downstream end is

$$T_{50} = [1 - (50/200)^{0.644}] (42 - 24) + 24 = 34.6°C$$

This value is then used to compute the viscosity of water and consequently the Reynolds number and friction factor at a particular position along the lateral.

The emitter flow function given by $q = kH^x$ is modified to include the emitter discharge sensitivity to water temperature, kt, and a measure of emitter variability, cv. The coefficient of emitter manufacturing variation, cv = sd/qa, is standard deviation divided by the average emitter discharge rate. Thus the emitter flow function becomes

$$q_i = (1 + Kt(T_1 - T_n) kH_i^x + (cv.qa.RV) \quad (16)$$

where RV is a random variable to place the value of emitter discharge anywhere within a normal distribution, just like the real situation in the field. Eqn. 16 considers the discharge rate dependence on water temperature, kt, but ignores the effects of emitter clogging.

Kt is the % change in discharge per degree rise in water temperature. Values may range from -0.68 to 6.8, but do not usually exceed 1.4%. Parchomchuk (1976) found high kt values for laminar flow emitters: 1.4 for microtubes, and 1.2 for spiral passages. For turbulent flow emitters, he found kt values of 0.032 for orifice emitter 1.5 mm long, and 0.129 for 12.7 mm long orifice. Vortex emitter has negative kt value of -0.267.

Coefficient of manufacturing variation, cv depends on the emitter design, construction material and manufacturing process. It is the ratio of standard deviation to the mean discharge rate measured at the standard pressure (usually 100 kPa for non-compensating emitter) and standard temperature (usually 20°C) with no emitter clogging. Normally 50 discharge tests made on 50 unused samples of the same emitter are required.

Even though values up to 0.4 have been measured, cv is typically below 0.15. Solomon (1977) presented values for a number of different types of emitters. Decroix and Malaval (1985) found cv=0.22 for labyrinth long path non-compensating emitters and 0.15 for short path compensating emitters.

Bui and Kinoshita (1985) found 0.32 for dual chamber, 0.30 for single tape and 0.13 for single chamber emitter tube.

Reynolds number may be expressed in terms of the water temperature using the expression for kinematic viscosity given by Boor *et al.* (1968), as follows:

$$Re = 198.7\ Qt\ (1 + 0.03368T + 0.000221T^2)/D \tag{17}$$

where Qt is the total flow rate in l/h at a particular point along the lateral line, T is temperature in degrees Celsius and D is internal pipe diameter in mm.

The uniformity of water application by micro-irrigation is a function of: 1) hydraulic variation caused by elevation changes and friction losses along the distribution lines, and 2) emitter discharge non-uniformity caused by emitter manufacturing variability, emitter clogging, temperature changes and aging.

In the step by step analysis, Christiansen uniformity coefficient is used.

$$CU = 100(1-\Sigma|qi-qa|)/\Sigma qi) \tag{18}$$

where Σqi is the sum of all discharges from emitter i=1 to N, qa is the average discharge rate $\Sigma qi/N$, N is the total number of emitters, and $\Sigma|qi-qa|$ is the sum of absolute deviations of individual emitter discharge from the mean discharge. CU may be alternatively expressed as

$$CU = 100(1-(\Delta q/qa)) \tag{19}$$

where qa is the mean discharge, Δq is the mean absolute deviation of discharge rates.

ANALYSIS

The step by step approach was compared to the conventional method. For purposes of comparison, the following assumptions were made in the hydraulic analysis using the conventional approach:

Water temperature was kept constant at 20°C. Local loss due to emitter protrusion, Le = 12% for insert emitters with average barb size equally spaced 1 m apart on 16 mm ID PE tubing. K2 emitters with flow function $q = 0.434\ H^{0.631}$ were used. The emitter discharge q = 2.0 lph (i.e. at H = 11.26 m). In the case of Darcy-Weisbach equation, the friction factor for turbulent flow was extended to the laminar region. Hazen-Williams roughness coefficient C was taken to be 130. Lateral length L = 200 m on a level ground, He=0. Reduction coefficient F was calculated for each equation since it depends on the number of outlets and flow rate exponents. Eqns. 8, 9 and 10 were also used in the Darcy-Weisbach equation and noted as DW_K, DW_{BS} and DW_D, respectively.

Results of head loss calculated using the conventional approach with and without considering emitter friction for various equations are shown in Table 1.

TABLE 1
Head loss calculated using different equations

Equation	HW	DW_B	DW_{BS} (Eqn.9)	DW_K (Eqn.8)	DW_D (Eqn.10)
Without Le	2.52	2.42	2.64	2.66	2.73
With Le	3.49	3.31	3.59	3.61	3.72

The Hazen-Williams formula and Darcy-Weisbach equation with friction factor from Blasius give a lower frictional head loss than the more recent results on polyethylene pipes. Typically later expressions give more than 10% higher head loss.

Lateral line head loss may be underestimated in excess of 25% when emitter protrusion is not included in the analysis. This shows the significant contribution of emitter barb protrusion in the head loss of a lateral line. The larger protrusion gives more resistance to flow, thus higher friction loss. However, the shape of the protrusion is a more important factor than its size in influencing the head loss across emitter connection (Amin 1990).

Friction factor for the turbulent flow regime is usually extended to the unstable and laminar flow regimes of the lateral. It was found that the total head loss in a lateral is the same irrespective of whether one, two or three friction factor equations were used for the three flow regimes. This justifies the use of the expression for λ in the turbulent flow regime extended to the laminar region.

A step by step analysis from the downstream end for elevation head, emitter discharge, Reynolds number of flow in the lateral and total head loss produced results as shown in *Fig. 3*. Head loss falls in between those found by the conventional method with and without considering friction from emitter protrusion.

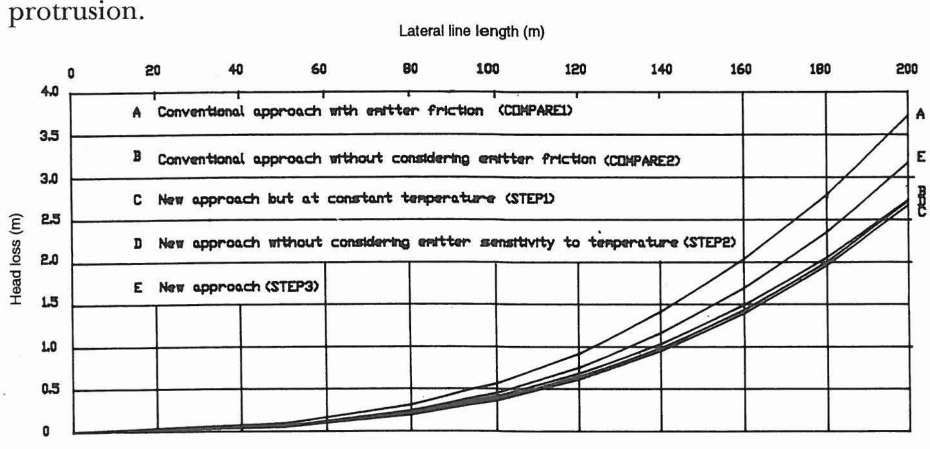

Fig. 3. Results of program COMPARE and program STEP using k2 emitters 1 m apart on 16 mm PE lateral

PROGRAM HAMIL

A micro-computer program known as HAMIL (or Hydraulic Analysis of Micro-Irrigation Lateral) was developed to ease lateral design. It is a step by step analysis using friction factor for isolated roughness flow regime. Friction factor can be selected based on the lateral used, viz. tubing without emitter protrusion, 15 mm ID PE and 13 mm ID PE.

Based on previous studies on 14.3 mm diameter PE pipe fitted with insert emitters which have 5 mm depth of protrusion, Svehlik (1982) derived an equation for isolated roughness flow for various spacings as follows:

$$\lambda = 0.327\, S^{-0.161}\, Re^{-0.238\, S^{0.062}} \tag{20}$$

Eqn. 20 may be used for friction factor to replace that of Blasius in the Darcy-Weisbach equation for head loss. *Fig. 4* shows a plot of the equation for various emitter spacings in a 14.3 mm diameter lateral. The plot shows good agreement with experimental data. Data points for plain tubing (without emitter connection) from Dent (1985) are included in *Fig. 4*. Eqn. 20 gives good fit even though the two experiments were carried out using different emitters.

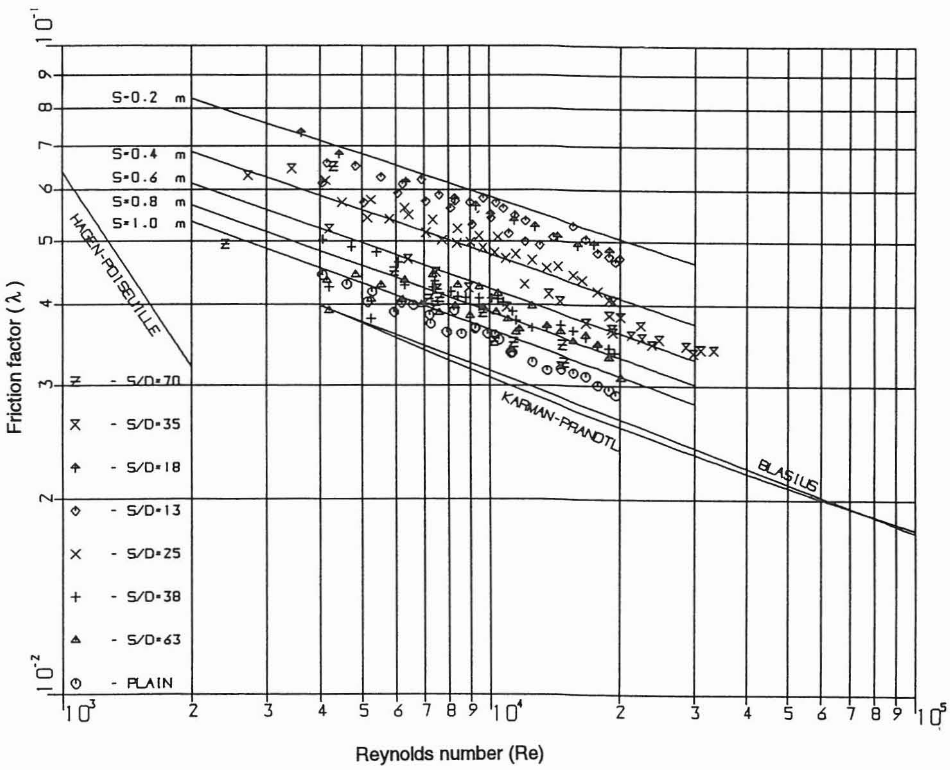

Fig. 4. Friction factor for isolated roughness flow

Studies on 13 mm ID PE laterals fitted with typical insert emitters give a significantly larger head loss in the lateral (Amin 1993). The following equation was derived from the data obtained.

$$\lambda = 0.605\ S^{-0.069}\ Re^{-.284\ S^{0.111}} \tag{21}$$

As shown in *Fig. 5*, the equation fits experimental data well for spacings of 1 m or less. At larger spacings, the data points seem to cluster above the smooth line around the values for S=1.0 m.

Since the size of lateral and presence of emitter barb protrusions in the pipe are important factors, the program allows three possible friction factor expressions to be selected: Eqn. 10 for PE pipes without emitter barb connections; Eqn. 20 for 14-19 mm ID PE with insert emitters and Eqn. 21 for 12-13 mm ID PE. For spacings greater than 2 m, Eqn. 10 can be used because there was not much observed difference in the data points at greater spacings.

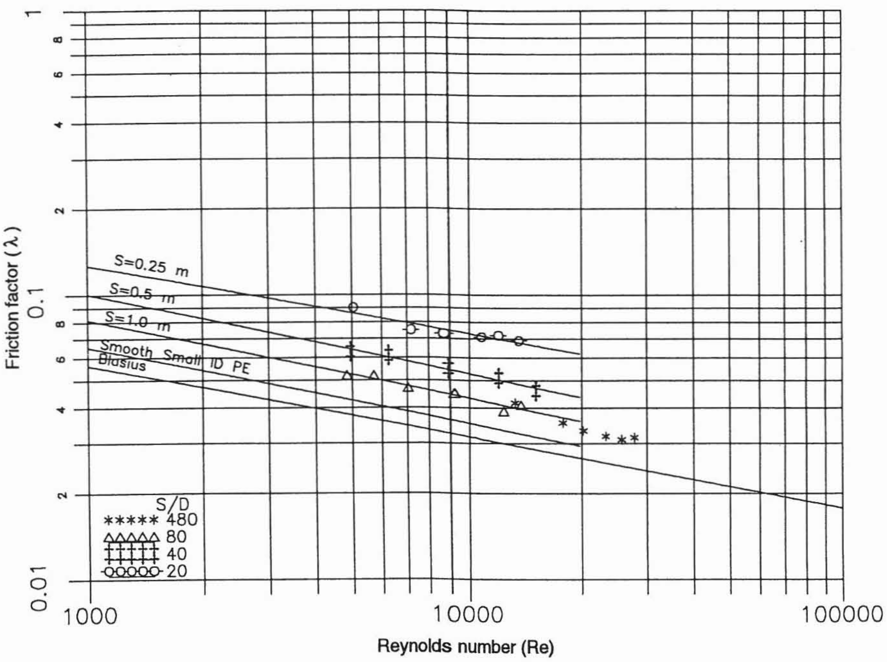

Fig. 5. Friction factor for isolated roughness flow regime in 13 mm PE lateral with truncated cone shaped protrusion at various spacings (Eqn. 21)

In program HAMIL, emitter discharge variability caused by manufacturing variation, pressure variation and land slopes are included. The effects of temperature on emitter discharge and lateral flow are also considered. The analysis starts from the downstream end of the lateral with a known pressure head for the desired emitter discharge.

Input data on lateral, emitter, temperature and land slopes are required: Lateral size and length, number of emitters and spacing, the operating pressure head, the end to end change in water temperature of the lateral, and the length and slope of reaches. There is provision for four reaches of different slopes for a lateral. Other information needed are emitter flow function, emitter sensitivity to temperature, coefficient of manufacturing variation, and the desired pressure ratio for uniformity.

The end to end water temperature change in the lateral line should be estimated from local experience. Local data should be consulted for daily and seasonal variations in water temperature in the water source, manifold and laterals which may be buried or exposed. The prevailing temperatures during the critical stage of crop growth should be used. For design purposes, in the absence of local data, the following ΔT may be used: Exposed laterals, no shading from crop canopy, 15-20°C; with some shading or cloud cover, 10-15°C. Buried, or under cloud cover or shade from canopy, 5-10°C.

Unlike the conventional approach, the emitter discharge in the new approach is not fixed. Value of q varies with changes in pressure, temperature and elevation. In program HAMIL a value Z drawn at random from the standard normal variate is included.

The following calculations are carried out in sequence from one emitter to the next: elevation head, temperature, emitter discharge, Reynolds number of the flow in the lateral, head loss, Christiansen uniformity coefficient, and maximum and minimum pressure head. Printouts of results show length, head, pressure ratio, flow rate, uniformity coefficient, temperature, Reynolds number, total head loss and total elevation head. A sample printout is shown in the appendix for a 200 m long 16 mm diameter lateral fitted with typical 2 l/h insert emitter spaced 1 m apart, and land slope changes every 50 m.

CONCLUSIONS

From the results of the study, the following conclusions can be drawn:

1. The Hazen-Williams formula and Darcy-Weisbach equation with friction factor from Blasius give lower frictional head loss compared to more recent results on polyethylene lateral pipes. Typically later expressions give more than 10% higher head loss.
2. Micro-irrigation lateral design should consider emitter barb protrusion and the effects of water temperature on emitter discharge and pipe flow. Ignoring emitter protrusion may lead to an underestimation of head loss in a lateral in excess of 25%.
3. Since water temperature affects flow rates in the lateral and some emitters, the step by step approach with friction factor for isolated roughness flow regime which considers the effects of viscosity on the lateral flow rate and emitter discharge along the lateral gives a more accurate result than the conventional method. Thus the new approach should be used for improving the energy, water and material use efficiency of a micro-irrigation system.

4. The micro-computer program known as HAMIL developed using the new approach is convenient to use. The factor for dividing flow F and equivalent length emitter barb friction loss Le is not needed in the step by step analysis.
5. Designers who resort to the conventional approach without the convenience of computing facilities should select the roughness coefficient that reflects the combined roughness caused by pipe wall as well as emitter barb protrusion.

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APPENDIX

PROGRAM H.A.M.I.L. BY M.S.M. AMIN 1993

HYDRAULIC ANALYSIS OF MICRO IRRIGATION LATERALS
STEP BY STEP ANALYSIS CONSIDERING FRICTION FACTOR FOR ISOLATED ROUGHNESS FLOW REGIME AND EFFECTS OF TEMPERATURE ON FLOWRATES

NOTE: ANALYSIS STARTS FROM THE DOWNSTREAM END OF THE LATERAL

INPUT VARIABLES

D= 16 mm, L= 200 m, S= 1 m, H= 10.5 m, N= 200,
K= .43 X= .63 CV= .1 KT= .01 T2=20 C T1= 40 C
REACH LENGTHS (m) : LR= 5050 50 50
REACH SLOPES (m/100m) : SR= 1 -2 3 -4

RESULTS OF HYDRAULIC ANALYSIS OF MICRO-IRRIGATION LATERAL

L (m)	H (m)	RH	QT (1ph)	T (C)	RE -	HFT (m)	HET (m)	CU (%)
10.00	10.59	1.01	22.58	37.09	715.94	0.00	0.10	98.20
20.00	10.70	1.02	45.13	35.46	1385.58	0.01	0.20	98.32
30.00	10.80	1.03	67.09	34.11	2004.28	0.01	0.30	98.14
40.00	10.92	1.04	88.87	32.91	2590.73	0.03	0.40	97.99
50.00	11.05	1.05	111.05	31.81	3165.02	0.06	0.50	97.97
60.00	10.92	1.05	132.81	30.79	3705.01	0.11	0.30	97.92
70.00	10.78	1.05	153.88	29.83	4206.41	0.16	0.10	97.62
80.00	10.65	1.05	174.76	28.91	4684.75	0.24	-0.10	97.29
90.00	10.54	1.05	195.42	28.04	5140.43	0.33	-0.30	97.04
100.00	10.45	1.06	215.76	27.20	5572.25	0.44	-0.50	96.70
110.00	10.83	1.06	235.90	26.39	5984.38	0.57	-0.20	96.40
120.00	11.28	1.08	256.73	25.61	6399.86	0.72	0.10	96.44
130.00	11.75	1.13	278.06	24.85	6813.77	0.90	0.40	96.56
140.00	12.25	1.17	299.51	24.10	7216.65	1.10	0.70	96.64
150.00	12.78	1.22	321.56	23.38	7620.56	1.33	1.00	96.65
160.00	12.71	1.23	343.28	22.68	8003.55	1.60	0.60	96.73
170.00	12.60	1.23	364.72	21.99	8367.36	1.89	0.20	96.82
180.00	12.52	1.23	386.55	21.31	8727.94	2.22	-0.20	96.85
190.00	12.48	1.23	407.80	20.65	9063.75	2.58	-0.60	96.89
200.00	12.48	1.23	429.13	20.00	9390.10	2.98	-1.00	96.94